Dynamics and morphology in the inner regions of spiral galaxies

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CHAPTER 1

Introduction and Summary

The formation and evolution of galaxies represents one of the foremost questions in the understanding of the Universe. Galaxies are not static structures. They form at a certain time during the history of the Universe, and evolve with time. Given that galaxies are found in a variety of shapes and properties, studying the properties of galaxies is best carried out when they are sub-divided into different morphological types. In the 1920s, Edwin Hubble introduced the classification scheme illustrated in Fig. 1.1 which classifies most galaxies into categories of elliptical, normal spiral, barred spiral, and irregular galaxies, and then subdivided these categories with respect to properties such as the amount of flattening for elliptical galaxies and the size of the bulges and the nature of the arms for spiral galaxies (Hubble 1926). The Hubble sequence has often been interpreted as an evolutionary sequence with galaxies evolving from right to left. Recently there are more and more studies that find that some galaxies have undergone significant morphological transformation over cosmic time. It is found that, in the nearby Universe, more field disk galaxies are of earlier Hubble type than at higher redshift (Lilly et al. 1998). Also a large number of faint blue galaxies have been detected at intermediate redshift, which are believed to have evolved by now to red dwarf ellipticals (Ellis et al. 1997). Last but not least, it has been known for quite some time that spiral galaxies after merging can form elliptical galaxies (Toomre & Toomre 1972).

The interesting puzzle is now to use these transformations to learn more about what happens with these objects through mergers of galaxies, interactions with companions, or by internal dynamical processes. Do galaxies evolve along the Hubble sequence, and in which direction?

As stars orbit around a galaxy, they can only change their velocities in a continuous manner, dictated by acceleration due to the gravity. The density of stars is so low that they do not collide but move in the collective gravitational field surrounding

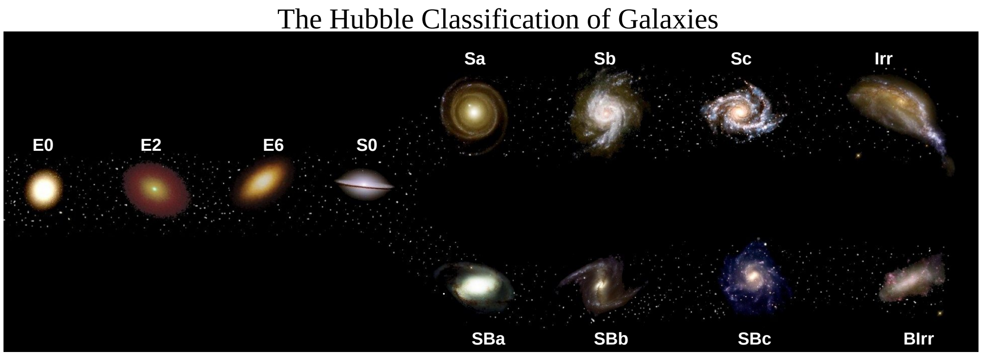

Figure 1.1: Hubble's galaxy classification scheme is presented here. Throughout this thesis we focus on the properties of the Sa-Sb galaxies.

them. Stellar velocities in disk galaxies can be derived by measuring the Doppler shifts of the stellar absorption lines. At every position on the sky one can measure the motions of the stars and their locations perpendicular to the line-of-sight. Consequently, one can obtain the stellar kinematics in a galaxy by analysing spectral information, with the aim of characterising the line-of-sight velocity distribution (LOSVD) which is the probability of finding a star with given projected velocity at a certain position on the sky. The LOSVD is the only measurable kinematic quantity, since for galaxies outside the immediate surrounding of the Milky Way, the light from the smallest resolvable parts include contributions from more than one star. Analysing the LOSVD, one can get information about the gravitational potential, by taking into account the distribution of the line-of-sight velocities.

In the regions between stars, galaxies host a significant amount of gas and dust. The large-scale distribution of the various components of the interstellar medium is best studied in external galaxies, since they can be seen as a whole. Of particular interest for our study is the interstellar gas, which constitutes more than 95% of the total mass of the interstellar medium (the rest being dust). Constituents of the gas include neutral and ionised hydrogen, neutral and ionised atoms of other elements, molecules, and energetic charged particles. All atoms and molecules will emit (or absorb) radiation of specific wavelengths due to transitions between their various atomic and molecular states. In the case of neutral hydrogen (H I), the hyperfine transition emits or absorbs at $\lambda = 21.11$ cm.

Observations of H I have proved to be an invaluable astronomical tool for studying large-scale interstellar medium kinematics, dark matter, the effects of interaction between galaxies, the effects of magnetic fields, and the effects of perturbations on the gravitational potential (e.g., Sancisi & Allen 1979; van der Kruit & Allen 1979; Bosma 1981; Binney & Merrifield 1998, §8.2; Sofue & Rubin 2001). Since the resolution of the H I observations is usually of the same order as the disk scale length, very little small-scale structure in the velocity field can be observed in this manner. Improved spatial resolution can be achieved when using CO as a tracer of gas (e.g., Turner & Hurt 1992), but such gas is usually only found in the spiral arms in the very centre. To achieve better spatial resolution one needs to go to the optical, where Hα have been used as an efficient tracer of gas (e.g., de Vaucouleurs & Pence 1980). In the optical, emission-lines in particular trace the warm ($T \sim 10^4$K) ionised and excited component of the interstellar medium. The gas has usually been excited by ionising radiation from either hot stars or an active galactic nucleus (e.g., Osterbrock 1989), or sometimes the excitation is due to a passing shock wave (e.g., Unger et al. 1987).

Past studies of the optical observations have addressed questions such as the evolution of large-scale as well as nuclear spiral arms and bars, metallicities within disks, gas diagnostics, comparison between stellar and gaseous dynamics, the effect of shocks, and mass transfer into the active galactic nuclei (e.g., Zaritsky, Kennicutt & Huchra 1994). As for the stars, optical stellar kinematics does not reach the large galactocentric radii reached by H I observations. One can, however, study large galactocentric radii using probes like PNe, Globular Clusters.

In this thesis, we focus on the inner regions of barred as well as unbarred spiral galaxies, and aim to better understand to what extent non-axisymmetric features such as bars determine the evolution of a galaxy. It is known that non-circular motions due to bars transfer matter towards the centre of galaxies, which may participate in the fuelling process of an active galactic nucleus (see Combes 2001 for a review on fuelling the AGN). It is also known that bars evolve and that they are subject to, e.g., thickening or bending (Sellwood 1996), and that some bars might eventually self-destruct and become part of the bulge (e.g., Norman, Sellwood & Hasan 1996; Kormendy & Kennicutt 2004). It is however not known what the morphology or the dynamics of an evolved bar is. Moreover, it is not known to what level a bar participates in the fuelling of an active nucleus. These questions have remained unanswered, since it has been observationally very difficult to test the existing theories and to recognise the predicted features such as elliptical streaming caused by bars. It is still not well known what the potential in the inner region looks like. Is it generally axisymmetric, non-axisymmetric, triaxial or bar like?

We try to find answers to these questions by using not only traditional photometry, but also, for the first time, two-dimensional spectroscopy of the central kiloparsecs of a large sample of spiral galaxies. The answers shed light on the origin of bulges, on the formation of galaxies as a whole, and on the fuelling of the central black hole. The second chapter discusses the results of the photometry. The following three chapters deal with the results of Integral Field Spectroscopy, where we investigate the kinematics and dynamics of the ionised gas and stars.

Chapter 2

We have studied NIR images of a sample of 70 spiral galaxies, and found with statistically significant indications that the inner features in bulges of late-type spirals are more elongated than those in early-type spirals. The result was tested by comparing the projected and the average ellipticities in these galaxies, for which we found no difference. These results probably indicate that bulges of later-type spiral galaxies contain more elongated features, like nuclear bars, than bulges of early-type spirals. Our results could be explained if bulges of late-type spiral galaxies are formed primarily through secular evolution of bars, while this would not be the case for earlier-type bulges. It is however too early to derive more conclusions about secular evolution, since a much better understanding of this process is required.

Chapter 3

With the aim of improving our understanding of the dynamics of bars and the effects of bars on host galaxies, we have followed up the imaging study by a spectroscopic study. We made use of the `SAURON` Integral Field Spectrograph and have obtained the distribution and the full kinematic signatures of stars as well as of the gas in the central kiloparsecs of 24 early-type (S0a-Sab) spiral galaxies. We found that two-dimensional spectroscopy provides a wealth of information about gas and stars. By disentangling stars and gas, we derive the kinematics of both components independently. The maps show the potential of `SAURON` for delving into the complex kinematic features associated with the role of bars in the formation history and evolution of spiral galaxies. Studying the two-dimensional stellar line-of-sight velocity distribution, and the gaseous emission-line kinematics, we found evidence for the presence of multiple components such as kinematically decoupled cores and misaligned or counter-rotating inner disks, as well as strong deviations from pure rotation. A simple investigation of the velocity fields has shown that disk-like rotation is prominent in 21/22 spirals, and that about half of all spiral galaxies host inner disk-like structures. Moreover, we have found that Seyferts+LINERs in the sample have central gaseous velocity dispersions which exceeds that of its stellar counterpart. The non-active galaxies in the sample do not show this behaviour. Coinciding with this velocity dispersion discrepancy, we find that in all cases the stars rotate slower than the gas.

In an attempt to study the observed deviations from circular motions, we focused on studying the gas velocity fields, to which we applied a harmonic decomposition technique. This type of analysis can be calibrated with tested analytical models and provides clues about gravitational potential perturbations. One important aspect of this approach is to detect and quantify radial flows and to understand the re-location of matter and the fuelling of AGN by non-axisymmetric potentials. As a result of this, we have been able to recognise signatures of bars and spiral arms on two-dimensional velocity fields. We have detected clear kinematic signatures of bars in 54(±5)% of all our sample galaxies. Moreover, applying the harmonic decomposition formalism has allowed us to investigate the frequency and amplitude of minor-axis rotation in our representative sample. Stellar and gaseous misalignment has been detected in $\sim$ 63(±5)% of spiral galaxies in our sample. Thus, combining all our galaxies with the indication of non-axisymmetric kinematics, we find that 95(±1)% of our galaxies are consistent with a non-axisymmetric structure.

Chapter 4

To carry out a more detailed study of the effect of bars on an observed velocity field, we chose to more fully analyse the two-dimensional `SAURON` data of a clearly barred galaxy (NGC 5448). We were able to successfully model the bar and reveal the effects of a lopsided perturbation co-existing with the bar. We also unveiled a central gas disk which is probably formed by mass transferred to the centre by the bar. It was known that NGC 5448 hosts a considerable amount of dust which is asymmetrically distributed all the way to the centre, and we were able to also investigate the effects that such an asymmetric dust distribution causes in the observed stellar and gas velocity fields.

Chapter 5

To then better understand the role of bars on fuelling an active nucleus, we studied the stellar and the gaseous kinematics of the notorious Seyfert 2 galaxy NGC 1068 over a two-dimensional field covering the entire inner (secondary) bar seen in the near-infrared. We detected a kinematical decoupling of the central 350 pc in a reanalysis of previously published long-slit data. We first observed a flattening of the h_3 profile indicating a change of orbital structure within that region, and then detected a flattening in the central part of the stellar velocity dispersion profile. A detailed comparison of our data with previously published HST, Hα and CO data, in which we found excellent agreement between all datasets. We also found evidence that the inner near-infrared bar has driven gas within its ILR, thus forming a relatively cold stellar system within the central few hundred parsecs.

Some Future Prospects

We have developed an analytic method to recognise and quantify bar signatures in observed velocity fields. We were able to apply the method successfully to a sample of early-type spiral galaxies, and discovered that stars and gas are misaligned in a significant fraction of these systems. Further development of these studies can be pursued on two fronts. The first is quantification of the non-circular motions, and the other being the role of non-axisymmetric structures on the dynamics and morphology of the host galaxy and on the fuelling of the AGN, if present. In connection with the study of NGC 1068, we are currently emphasising the effect of the secondary bar, via a qualitative comparison of the SAURON data with an N-body + SPH simulation in which the bar shows clear signatures in all first four moments. A number of simulations with different initial parameters are in progress, and are aimed to be ready in the near future. In connection with the general properties of early-type spiral galaxies, we aim to carry out a more detailed analysis of the entire sample to establish the presence of substructures such as KDCs and bars, and to understand the origin of counter rotating components. To better understand the role of bars, we have also started a study which involves mapping (with SAURON) the kinematics and stellar populations of a sample of nearby early-type barred galaxies, over the entire extent of their bar.

The entire spiral sample, presented in this thesis, has been observed in the *V* and *I* medium-field filters over a very large field. This homogeneous set of images covers the entire extent of all galaxies, and will provide invaluable information to study correlations between the central and global properties, and to identify and characterise morphological counterparts to kinematic subcomponents. In particular, the size, brightness, and boxiness/diskyness of bulges are known to correlate with the Sérsic shape parameter, nuclear cusp slopes, and nuclear black hole masses. Moreover, high resolution imaging and spectroscopy of the central parts of nearby galaxies have shown that galactic nuclei present a rich variety of structures: nuclear disks, double nuclei, massive black holes, and small decoupled cores. In this context, there is great potential in complementing the SAURON data with data from other IFUs which operate with adaptive optics, such as OASIS and in the future, the Multi Unit Spectroscopic Explorer MUSE, in order to obtain kinematic maps with higher spatial and spectral resolution.